Time Transfer Methodologies for International Atomic Time (TAI)

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While there are many forms of time-transfer, the most precise long-distance forms currently used for the generation of International Atomic Time (TAI) and Coordinated Universal Time (UTC) involve either GPS or Two Way Satellite Time and Frequency Transfer (TWSTFT). This paper gives a brief description of their current and future capabilities, with emphasis on how their uncertainties affect UTC. Some of these uncertainties are due to inherent modeling or receiver instabilities, while others can be reduced through temperature and humidity stabilization, electronic impedance matching, and multipath minimization. The residual time-transfer uncertainties directly affect the uncertainties in each individual laboratory's realization of UTC.

GPS is the best-known means of precise time transfer, and the introduction of Common-View GPS (CV) contributed significantly to the great increase in the stability of TAI over the last 15 years. GPS pseudorange observations are currently adjusted by correcting the broadcast orbital and ionosphere delay information with post-processed values, and reduced in common-view mode. However "melting-pot" techniques have been shown to be more precise over long baselines and "P3" observations, using dual-frequency carrier-phase receivers, allow use of measured ionosphere delays. P3-links have been used by the International Bureau of Weights and Meaures (BIPM) for TAI-generation; plans to greatly increase their role have been circulated. The continuous GPS observations are supplemented by periodic receiver calibrations, which have accuracies of several ns. Greater precision (20 ps), but not significantly greater accuracy, would be attainable if carrier-phase GPS techniques were employed [1]. Several institutions, and in particular the International GNSS Service (IGS), routinely provide publicly available carrier-phase based timing solutions in near-real time [2]. Other institutions will reduce any laboratory's data for free via an automated procedure. A few institutions, such as JPL/NASA and NRCan, provide real-time carrier-phase based time transfer as well [3,4]

Beginning in 2000, time-transfer links using TWSTFT replaced some GPS links as the primary operational link, and currently over half the clocks used for TAI-generation are linked to other sites via a direct TWSTFT link. TWSTFT links can be calibrated to achieve slightly subnanosecond absolute time transfer, with a precision in the range of a few hundred ps [5]. Carrier-phase TWSTFT holds the promise of ps-level precision, but this promise has not yet been realized in any system [6].

The generation of TAI involves merging information via dissimilar links, which complicates the relevant statistical approach and increases the dependence of TAI upon the stability of the time-transfer equipment at those "pivot sites", which are linked to some laboratories via TWSTFT but linked to other laboratories via GPS. The data from the links are used to transfer the time to generate UTC, which expressed as *UTC – UTC (k).* The first step in this process is to generate the free atomic time scale (EAL). EAL is defined using the ALGOS algorithm [7-9] as:

$$EAL(t) = \sum_{i=1}^{N} w_i \left[h_i(t) + h_i'(t) \right] \qquad (1)$$

where N is the number of the atomic clocks, w_i the weight of the clocks, $h_i(t)$ is the reading of clock H_i at time t, and $h_i'(t)$ is the prediction of the reading of clock H_i to guarantee the continuity of the time scale. The weight attributed to a given clock reflects its long-term stability, since the objective is to obtain a weighted average that is more stable in the long term than any of the contributing elements [10]. The ALGOS software package is used in the Time Section of the BIPM in order to generate EAL, and afterwards UTC is generated by the addition of leap seconds and frequency steers. The data used by ALGOS take the form of the time differences between readings of clocks, written as:

$$x_{i,j}(t) = h_j(t) - h_i(t). \qquad (2)$$

This results in a system of N equations and N unknowns, the solution yielding:

$$x_j(t) = EAL(t) - h_j = \sum_{i=1}^{N} w_i \left[h_i'(t) - x_{i,j}(t)\right] \qquad (3)$$

If we choose a particular clock H_j, we can see that the difference between that clock and EAL depends on weights, clock prediction, and measured clock differences. The predictions and the weights are fixed by appropriate algorithms based on the past clock behavior and therefore can be considered as time-varying deterministic parameters. Suboptimal estimation of these parameters would affect the uncertainty of *TAI* as realization of the Terrestrial Time (*TT*), but they do not affect the knowledge of the difference between *EAL* and clock H_j. The measures $x_{i,j}$ are thus the only contributors to the uncertainties in x_j. We ignore the contribution of the uncertainty given by measurements of clocks located inside the same laboratory, since they are both negligible and indistinguishable from the noise of the individual clocks. The generation of UTC from EAL through the addition of pre-determined leap seconds and frequency steers does not add to the uncertainty. The uncertainties of [*UTC* – *UTC* (*k*)] are therefore identical to the uncertainties of [*TAI* – *UTC* (*k*)] and [*EAL* – *UTC* (*k*)], and we conclude that the uncertainties of the links among laboratories are the only source of the uncertainty of *UTC – UTC (k)*.

In order to correctly model the processes, the correlation of time-transfer links that share common sites must be estimated and accounted for. One approach is to use the law of propagation of uncertainties [11,12]. The uncertainty in the $x_j(t)$ can be found for a generic quantity y measured by means of direct measurements of the input quantity x_i,:

$$y = f(x_1, x_2, ..., x_M). \qquad (4)$$

The expression of the law of the propagation of uncertainty [12] is given by:

$$u_y^2 = \sum_{i=1}^{M} \left(\frac{\partial f}{\partial x_i}\right)^2 u_{x_i}^2 + 2\sum_{i=1}^{M-1}\sum_{k=i+1}^{M} \frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_k} u_{(x_i,x_k)} \quad (5)$$

where the first term corresponds to the effect of the uncertainties of the input quantities x_i, and the second term accounts for the correlation between them.

In our case, we are interested in evaluating the uncertainty of the quantity x_k = [*EAL* – *UTC* (*k*)] which here plays the role of the indirect quantity *y*, and the uncertainty contributions are only due to the measurement noise of the links $x_{i,j}(t)$:

$$u_{x_j}^2 = \sum_{i=1}^{N} \left(\frac{\partial x_j}{\partial x_{i,j}}\right)^2 u_{x_{i,j}}^2 + 2\sum_{i=1}^{N-1}\sum_{k=i+1}^{N} \frac{\partial x_j}{\partial x_{i,j}}\frac{\partial x_j}{\partial x_{k,j}} u_{(x_{i,j},x_{k,j})} = \sum_{i=1}^{N} w_i^2 u_{x_{i,j}}^2 + 2\sum_{i=1}^{N-1}\sum_{k=i+1}^{N} w_i w_k u_{(x_{i,j},x_{k,j})} \qquad (6)$$

where $u_{x_j}^2 = u_{EAL-h_j}^2$.

The weights of the clocks are available from the BIPM Web site, and the uncertainty of links between the clocks [13] are published in *Circular T* (see the BIPM Time Section's FTP server at www.bipm.org). It can be demonstrated that the ALGOS algorithm would generate the same results if each laboratory's clocks were replaced by a single "equivalent" clock whose reading was the weighted average of the individual clocks and whose weight in EAL was the sum of the individual clock weights. However, even if the uncertainties of transferring time internally within the labs were not considered part of the noise of the individual clocks, the formula could still be applied, as the double summation would account for the 100% correlation of the time transfer noise between clocks in the same lab.

For application to the computation of UTC, we need to consider the correlations between the links. If all time transfer were achieved using a single system per site, and if all sources of noise were site-based, such as mostly happens for Melting Pot GPS, also termed All-in-View (AV) [14,15], then all possible links would obey the following closure relation:

$$x_{i,j}(t) + x_{j,k}(t) + x_{k,i}(t) = 0 \qquad (7)$$

In this situation, the noise of each site's time transfer system would be indistinguishable from the noise of its clocks. The dominant uncertainty would be given by the site noise and all the external clocks would be seen through that dominant noise independently of their location. This noise would affect *UTC –UTC (k)* itself according to the total weight of the site clocks, but due to the closure relation it would not affect the difference between the clocks of any other two sites. Therefore, in such a situation:

$$u^2_{UTC-UTC(k)} = (1 - w_k)^2 u^2_{k,k} \qquad (8)$$

where $u_{k,k}$ is the uncertainty of site *k*'s time transfer system.

Uncertainties in time transfer using GPS common view (CV) are largely, though not entirely, laboratory-based. However, even for CV observations made using every available satellite, closure violations will arise if simultaneous satellite observations are recorded at only two of the three sites. In such cases, orbit mis-estimation and receiver noise will contribute uncertainties, and any azimuth or elevation-dependent asymmetries in the multipath environment would cause both uncertainties and biases. Since calibration is achieved by an all-sky sampling that is systematically different from the sky-sampling of CV, systematic multipath will also lead to uncertainties. Despite these noise sources, the closure relation largely holds for common view, and the largest source of uncertainty is typically due to variations of the receiver system that are common to all the data. In a BIPM-sponsored study [15] of 40 triplets of European and North American sites, the median closure violation was about 1 ns RMS for CV, and only 350 ps RMS for AV.

For Two-Way Satellite Time and Frequency Transfer (TWSTFT), the noise is again largely site-dependent. Some closure violations can occur because the observations between pairs of sites are typically made at different spread-spectrum codes and slightly different frequencies. The largest source of closure errors is probably due to the fact that the received signals are shaped by the product of the transmitting and receiving bandpasses, while the delay and certain noise components such as the cable-dependent multipath can systematically vary over the bandpass [16]. However, such closure violations can be reduced somewhat through baseline-dependent calibrations. In those cases where a TWSTFT system is calibrated with GPS, the uncertainties in the calibration are determined by the uncertainties in the GPS calibration. For calibrated data, the median closure violation of 434 European and N. American site-triplets is 680 ps RMS.

Special situations arise when one site is a pivot site, connected to some sites by one technique and other sites by a different technique. Let us assume a bias *B* exists in the GPS equipment at the pivot site. In this case, it is easy to show that the bias would affect those laboratories linked to the pivot site through the GPS system as follows:

$$\Delta_{UTC-UTC(k)} = (1 - W_G)B \qquad (9)$$

where W_G is the sum of all the weights of the laboratories linked to the pivot site by its GPS system.

The bias would affect the pivot laboratory and those linked to it by the pivot's TWSTFT system as follows:

$$\Delta_{UTC-UTC(k)} = -W_G\ B \qquad (10)$$

Under the normal circumstances described in this paper, the existence of any biases would not carry any significant statistical implications, as they would be directly related to the tabulated uncertainties in the links themselves. However, the above equations illustrate the dependence of TAI and UTC upon the equipment at any such "crossover pivot", and in the case of equipment failure or aging, such dependencies can result in non-Gaussian behavior.

In order to optimize the use of time-transfer in TAI-generation, several algorithms are under consideration. One algorithm would be to use all available links, rather than the minimum required to generate TAI, in a large least squares fit in which bias-parameters would be associated with all crossover sites. The bias parameters represent the bias between the site's different systems (typically GPS and TWSTFT, but they could also be the difference between the SPS GPS receiver and a geodetic receiver), and the weighted average of those bias parameters would be constrained to be zero. The calibration of all links would be pre-set by a self-consistent methodology. More elaborate schemes are also possible, but the common theme is that TAI-generation can be improved through improved modelling and removal of the systematic errors. As our frequency standards become more precise and more accurate, such techniques will become more necessary.

REFERENCES

[1] D. Matsakis, K. Senior, and P. Cook, 2002, "*Comparison of Continuously Filtered GPS Carrier Phase Time Transfer with Independent GPS Carrier-Phase Solutions and with Two-Way Satellite Time Transfer,*" Proceedings of the 33rd Annual Precise Time and Time Interval (PTTI) Systems and Planning Meeting, 27-29 November 2001, Long Beach, California, USA, pp. 63-87.

[2] IGS Web pages are at http://igscb.jpl.nasa.gov/

[3] E. Powers, K. Senior, Y. Bar-Sever, W. Bertiger, R. Muellerschoen, and D. Stowers, 2002, *"Real Time Ultra-Precise Time Transfer to UTC Using the NASA Differential GPS System,"* submit to EFTF-02.

[4] F. Lahaye, P. Collins, P. Herous, M. Daniels, and J. Popelar, 2002, *"Using the Canadian Active Control System (CACS) for Real-Time Monitoring of GPS Receiver Clocks,"* Proceedings of ION-GPS 2001, 11-14 September 2001, Salt Lake City, Utah, USA.

[5] L. A. Breakiron, A. L. Smith, B. C. Fonville, E. Powers, and D. N. Matsakis, 2005, *"The Accuracy of Two-Way Satellite Time Transfer Calibrations,"* Proceedings of 36th Annual Precise Time and Time Interval (PTTI) Meeting, in press.

[6] B. Fonville, D. Matsakis, W. Shäfer, and A. Pawlitzki, 2005, *"Development of Carrier-Phase-Based Two-Way Satellite Time and Frequency Transfer (TWSTFT),"* Proceedings of 36th Annual Precise Time and Time Interval (PTTI) Meeting, in press.

[7] B. Guinot and C. Thomas, 1988, *"Establishment of International Atomic Time,"* Annual Report of the BIPM Time Section, **1**.

[8] P. Tavella and C. Thomas, 1991, *"Comparative study of time scale algorithms,"* **Metrologia, 28**, 57-63.

[9] C. Thomas and J. Azoubib, 1996, *"TAI computation: study of an alternative choice for implementing an upper limit of clock weights,"* **Metrologia, 33**, 227-240.

[10]J. Azoubib, *"A revised way of fixing an upper limit to clock weights in TAI computation,"* Working Document CCTF/01-14 of the 15th meeting of the CCTF (see *www.bipm.org*).

[11] W. Lewandowski, D. Matsakis, G. Panfilo, and P. Tavella, 2005, *"First Evaluation and Experimental Results on the Determination of the Uncertainties in |UTC-UTC(k)|",* Proceedings of 36th Annual Precise Time and Time Interval (PTTI) Meeting , in press.

[12] *Guide to the Expression of Uncertainty in Measurement* (International Organization for Standardization, Switzerland), 1993.

[13] J. Azoubib and W. Lewandowski, 2003, *"Uncertainty of time links used for TAI,"* in Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Meeting, 3-5 December 2002, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 413-424.

[14] M.Miranian and W. Klepczynski, 1991, *"Time Transfer via GPS at USNO,"* in Proc. of the 4th International Tech. Meeting of ION-GPS-91 (Institute of Navigation, Alexandria, Virginia), pp. 215-222.

[15] Z. Jiang and G. Petit, 2004, *"Applying GPS satellites all in view in Circular T,"* BIPM, TM132.

[16] J. Davis and G. de Jong, private communication.